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We report on shot noise measurements in carbon nanotube based Fabry-Perot electronic interferometers. As a consequence of quantum interferences, the noise power spectral density oscillates as a function of the voltage applied to the gate electrode. The quantum shot noise theory accounts for the data quantitatively. It allows to confirm the existence of two nearly degenerate orbitals. At resonance, the transmission of the nanotube approaches unity, and the nanotube becomes noiseless, as observed in quantum point contacts. In this weak backscattering regime, the dependence of the noise on the backscattering current is found weaker than expected, pointing either to electron-electron interactions or to weak decoherence.

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The quantum character of transport in mesoscopic conductors qualitatively modifies the behavior of both the average and the fluctuations of the current that flows through them [1]. If interactions between charge carriers can be neglected, an accurate description of such conductors is given by a set of transmission probabilities $\{T_n\}$ which characterize the scattering of carriers. This description has been tested successfully for current noise in various conductors, ranging from quantum point contacts (QPCs) [2], in which one can isolate one spin degenerate channel with a single tunable barrier, to superconducting/normal/superconducting (S/N/S) structures [3, 4, 5]. In coherent few channel double barrier systems, quantum interference have also been shown to modulate the transmissions [6]. However, shot noise in such Fabry-Perot electronic interferometers has not been investigated experimentally so far.

Single Wall carbon NanoTubes (SWNTs) can display a Fabry-Perot behavior [7, 8] when their coupling to metallic reservoirs is high enough. Due to the so-called K-K' (orbital) degeneracy, two transmissions $\{T_1, T_2\}$ are needed in general to characterize transport in these devices[7]. Therefore, the combined measurement of noise and conductance should allow a full characterization of any nanotube in this regime by determination of this set. Early measurements of current noise in carbon nanotubes have shown that it was dominated by extrinsic $1/f$ noise below $100kHz$ [9]. For this reason, few shot noise measurements are available. In ref. [10], the Coulomb blockade regime was investigated and significant departures from the predictions of the non-interacting theory were found. In ref. [11], very low shot noise was found in a bundle of SWNTs highly coupled to normal reservoirs, pointing to ballistic transport. Very recently, the high bias shot noise has been investigated in gated carbon nanotube based Fabry-Perot interferometers [12] and signatures of electron-electron interactions have been found.

In this letter, we report on shot noise measurements in gated SWNTs in the low energy Fabry-Perot regime [13]. This allows a reliable quantitative comparison with the quantum shot noise theory. The measurement frequency, ranging from $400kHz$ to $5MHz$, makes the intrinsic (shot) noise dominate. Cross-correlations techniques [14] and room-temperature ultra-low noise preamplification give the required sensitivity (see EPAPS for

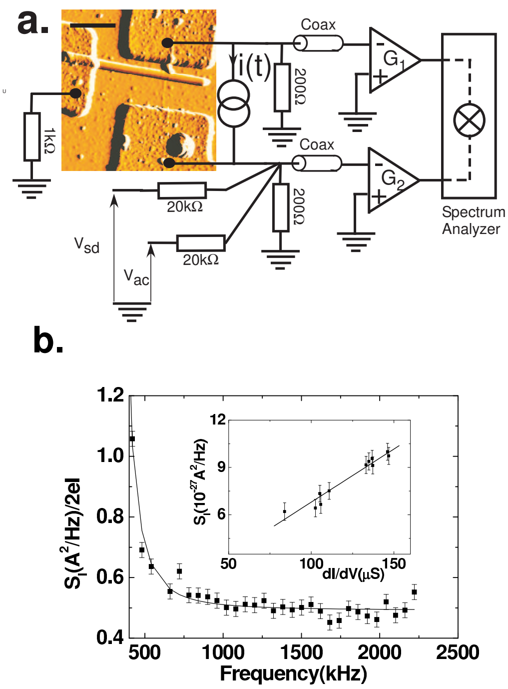

FIG. 1: a. Diagram of the circuit and AFM picture of the main sample presented in this paper. The MWNT is shunted by a $1k\Omega$ resistor placed on the PCB. The bar is $500nm$. b. Frequency dependence of the noise power spectral density measured at $V_{SD} = 1.1mV$ normalized by the Schottky value $2eI_{SD}$. The solid line is a fit with the formula $0.49 + 92.6/((f-300)^2 + (50)^2)$. Inset: Calibration of the background noise as a function of the conductance of the NT.

details). We find that the nanotube is well described by a non-interacting scattering theory accounting for the so-called K-K' orbital degeneracy commonly found in NTs and arising from the band-structure of graphene[15]. For the sample presented in this letter, the transmissions for the two channels are found to be equal within 10%. Near Fabry-Perot resonances, for which the transmission is close to 1, shot noise is strongly suppressed, as expected. However, its dependence with the backscattering current is found weaker than expected. This might be due to electron-electron interactions or weak decoherence.

The SWNTs are grown by chemical vapor deposition with a standard recipe [8]. They are localized with respect to alignment markers with an atomic force microscope (AFM). The contacts are made by e-beam lithography followed by evaporation of a $70nm$-thick Pd layer at a pressure of $10^{-8}mbar$. The highly doped Si substrate covered with $500nm$ doped SiO_2 is used as a back-gate at low temperatures. The typical spacing between the Pd electrodes is $500nm$ as shown in figure 1a. The two probe resistance of the obtained devices ranges from $10k\Omega$ to $200k\Omega$ at room temperature. For some samples, a third probe made of a Multi-Wall carbon NanoTube (MWNT) is placed with the help of the AFM tip on the top of the SWNT. Although the sample presented in this paper is of this kind, as shown in figure 1a, the coupling of the SWNT with the MWNT is very weak and can be omitted in the diagram. The temperature is $1.5K$ unless specified.

The circuit diagram (see figure 1a) yields the relationship between the voltage correlations $S_{cross} =< V_1 V_2^* >$ and the different current noise sources which contribute to the voltage fluctuations along the 200Ω resistors R_1 and R_2. It turns out that the main contributions to these fluctuations arise from the current noise S_I in the SWNT, the current noise of the two low noise preamplifiers respectively S_{n1} and S_{n2} and the Johnson-Nyquist noise S_1 and S_2 of R_1 and R_2, respectively . The complex value of S_{cross} is:

$$S_{cross} =\mid \alpha \mid^{-2} Z_1 Z_2^* \Big[- S_I + S_{off} \Big] \qquad (1)$$
$$S_{off} = \frac{Z_1}{R_{NT}}(S_{n1} + S_1) + \frac{Z_2^*}{R_{NT}}(S_{n2} + S_2)$$

with $\alpha = 1 + (Z_1 + Z_2)/R_{NT} + Z_1/R_{NT} + Z_1 Z_2/(R_{NT} R_{B1})$, where R_{NT} is the resistance of the SWNT, R_{B1} is the bias resistor of line 1, $Z_{1(2)} = R_{1(2)}/(1 + 2\pi j R_{1(2)} C_{1(2)} f)$, $C_{1(2)}$ the total capacitance in parallel with $R_{1(2)}$ and f the frequency. The linear behavior of the offset noise S_{off} as a function of T predicted by formula (1) for the sample presented in this letter is shown in the inset of figure 1b. A linear fit gives $S_{off} = (0.05 \pm 1.01 + 10.44T \pm 1.27T) \times 10^{-27} A^2/Hz$. Although the order of magnitude is correct, confirming that most of the signal comes from the noise of the NT, this is only in qualitative agreement with the expected offset of $21.1T \times 10^{-27} A^2/Hz$. We think that this can be explained by residual correlations arising from partial shielding of the parasitic signals in the band $0 - 10MHz$.

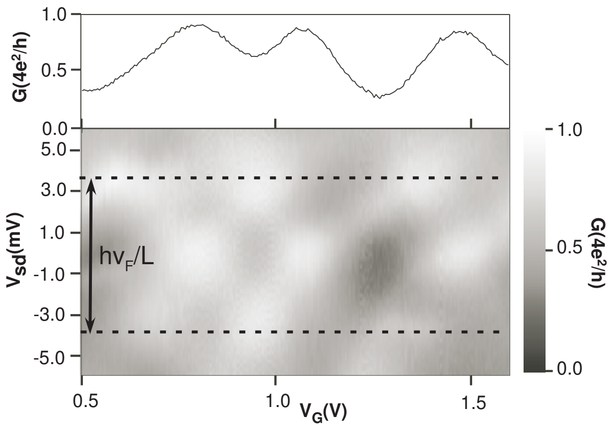

FIG. 2: Linear conductance and greyscale plot of the non-linear conductance. The characteristic checker-board pattern of a Fabry-Perot interferometer is observed. The level spacing (black double arrow) is of about $3.4meV$.

In general, the noise power spectral density displays a strong frequency dependence which is of $1/f^{\alpha}$ type [9, 17, 18] at frequencies of the order of $100kHz$ in nanotube devices. This extrinsic contribution points to the effect of charge traps which are effective in Coulomb blockade devices and could explain the observed noise in nanotubes at high current $\sim 100nA$ and high temperature $\sim 300K$. We have measured the noise on four different samples using the technique depicted above. Two of them (without the MWNT) had resistances of $250k\Omega$ and $1M\Omega$ respectively at room temperature and exhibited Poissonian noise, as expected for a conductor with a low transmission. For these samples, no frequency dependent noise was observed up to the highest bias voltage applied $V_{sd} = 30mV$ and down to the lowest frequency $580kHz$ at $1.5K$. The two others (with the MWNT) had a resistance of about $15k\Omega$ at room temperature and $V_G = 0V$. The resistance between the MWNT and the SWNT was about $1M\Omega$ at room temperature going up to about $10M\Omega$ at $1.5K$, turning these three terminal samples into essentially two terminal ones. We will focus on one of these samples for the remaining of the paper. Figure 1b displays the frequency dependence of the low temperature noise power spectral density S_I measured at $V_{sd} = 1.25mV$ for frequencies ranging from $421kHz$ to $2.221MHz$. This noise power spectral density has been normalized to the Schottky value $2eI$, I being the current flowing through the device and e being the elementary charge. From $1MHz$ to $2.221MHz$, $S_I/2eI$ is roughly constant, equal to 0.48, up to error bars. Below $1MHz$, the noise has roughly a $1/f^2$ dependence and the overall dependence is well fitted by the Lorentzian line shape

$0.49 + 92.6/((f - 300)^2 + (50)^2)$, with f in kHz. This shows that, at this bias, few fluctuators with a characteristic frequency of about $300kHz$ are excited. Below $V_{sd} = 1mV$, at our operating frequency of $2.221MHz$, the effect of charge fluctuators appears usually as an asymmetric noise curve with respect to the bias. This occurs rarely, about 5% of the gate voltage range, and produces a sudden change of S_I at constant V_{sd} when the gate voltage is swept. Data in this regime are not presented for clarity.

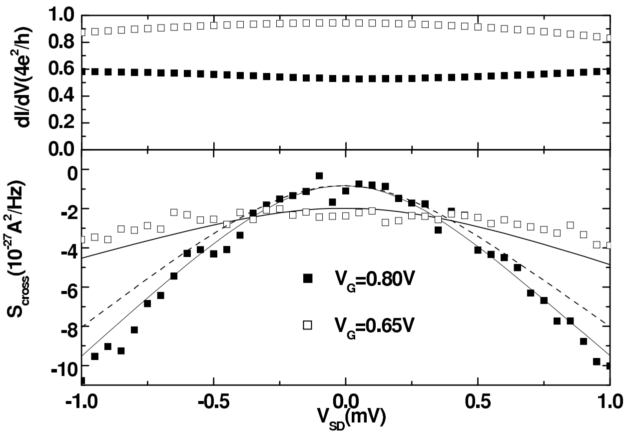

FIG. 3: Top: Non-linear conductance as a function V_{SD} for gate voltages $V_G = 0.65V$ and $V_G = 0.80V$. The filled squares correspond to $V_G = 0.65V$ and the open squares correspond to $V_G = 0.80V$. Bottom: Corresponding noise power spectral density as a function V_{SD}. The lines is formula (2) used for $T = 0.542$ and $T = 0.943$ which correspond to the zero bias value of dI/dV for $V_G = 0.65V$ and $V_G = 0.80V$ in units of $4e^2/h$.

The greyscale plot of the non-linear conductance dI/dV as a function of the gate voltage V_G and the source-drain bias V_{SD} is displayed on figure 1a. It exhibits the characteristic "checker-board" pattern of a Fabry-Perot interferometer [7, 8]. As shown on the side scale of the greyscale plot, the conductance is modulated from $0.3 \times 4e^2/h$ to about $0.95 \times 4e^2/h$. From the center of the white "squares" indicated by the dashed lines, one can extract a value of $3.4meV$ for the level spacing. This value is in good agreement with the lithographically defined spacing between the Pd electrodes of $500nm$, which yield $hv_F/2L = 3.34meV$ for a Fermi velocity of $8.10^5 m/s$. This value corresponds to the full SWNT length between the Pd contacts. Therefore, the MWNT contact does not split the SWNT into two pieces, as previously reported [19]. The irregularity of the pattern is likely due to weak scattering. As a consequence, the linear conductance exhibits sinusoidal oscillations with a changing amplitude, as shown on figure 2.

The lower panel of figure 3 shows the bias dependence of the current cross-correlations, for gate voltages of $0.65V$ and $0.80V$, for which the transmission is respectively of 0.542 and 0.943. The data are presented here without any background correction. For $V_G = 0.65V$, the noise power spectral density starts to display a linear behavior for a bias larger than $250\mu V$ which corresponds to $2k_BT \approx 258\mu eV$ at $1.5K$. For a lower bias, the noise power spectral density displays a rounded behavior and saturates. For $V_G = 0.80V$, a similar behavior is observed with a linear regime with a slope approximatively 3 times smaller than for $V_G = 0.65V$.

As shown on figure 3, the conductance is weakly non-linear in the range of $\pm 1mV$ where the shot noise is measured. The general formula for the shot noise in a quantum coherent conductor can in principle account for these non-linearities [1]. Since the maximum variation of conductance is 10% in the bias range considered, we will assume a constant conductance as a function of bias, for the sake of simplicity. In this case, if $T_{1,2}$ are the transmissions for the two different orbitals, the noise reads:

$$S_I = \frac{2e^2}{h}\Big(4k_BT\sum_{1,2}T_n^2 + \frac{2eV_{sd}\sum_{1,2}T_n(1-T_n)}{\tanh(\frac{eV_{sd}}{2k_BT})}\Big) \quad (2)$$

If orbital degeneracy is assumed ($T_1 = T_2$), the conductance completely determines the noise as only the total conductance in units of $4e^2/h$ enters in equation (2). Figure 3 bottom panel displays in solid curve the shot noise calculated using the *measured* zero bias total transmission (top panel) assuming full degeneracy. A quantitative agreement between the non-interacting theory and the data is found provided an offset of respectively $6.2 \times 10^{-27}A^2/Hz$ and $10.0 \times 10^{-27}A^2/Hz$ for $V_G = 0.80V$ and $V_G = 0.65V$ is incorporated in formula 2.

Combining conductance and shot noise has proved to be an efficient tool to probe the lifting of spin degeneracy in ballistic conductors transmitting a single orbital mode [20]. In the same spirit, we have investigated a possible lifting of the pseudo-spin orbital degeneracy in the present nanotube. We find an upper bound of about 10% for the difference in the transmissions of the two different orbitals for $V_G = 0.65V$. The dashed lines in figure 3 lower panel correspond to the case where $T_1 + T_2 = 2 \times 0.542$ but $T_1 - T_2 = 0.4$, in clear disagreement with the data.

The transmission dependence of formula 2 can also be tested by changing the transmission of the Fabry-Perot interferometer with the gate voltage. For this purpose, we have measured the noise for a finite bias voltage $V_{sd} = -0.7mV$ sweeping the gate voltage V_G from $0.65V$ to $1.25V$. In Figure 4a, the noise power spectral density normalized to the Schottky value is plotted (filled squares with the error bars) as a function of the gate voltage which is swept through two resonant levels. Each point is represented with the statistical error bar associated to a single averaging run. Note that the shot noise

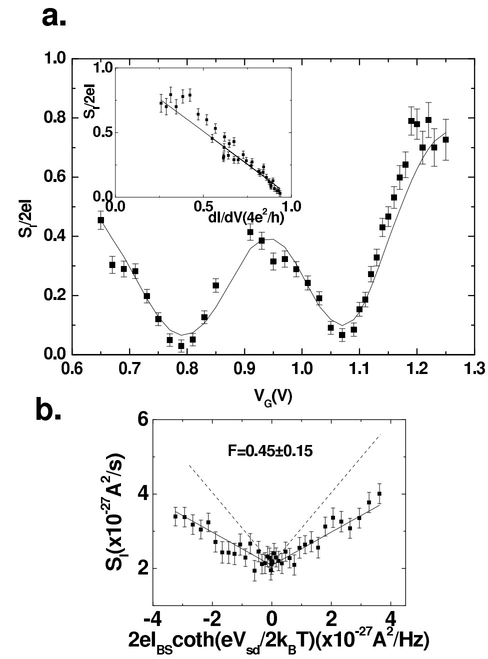

FIG. 4: Noise power spectral density measured (filled squares) at $V_{SD} = -0.7mV$ normalized by the Schottky value $2eI_{SD}$ as a function of V_G. The line is the theory with the assumption of full orbital degeneracy. Inset:Noise power spectral density measured (filled squares) at $V_{SD} = -0.7mV$ normalized by the Schottky value $2eI_{SD}$ as a function of the measured transmission. The observed linear behavior is in good agreement with the theory (line). b. Noise power spectral density as a function of the backscattering current. In solid lines , the linear fit gives $F = 0.45 \pm 0.15$. In dashed lines, the two-terminal non-interacting theory ($F = 1$)

contribution is obtained here by substraction of background noise, according to the fitted linear behavior of the inset of figure 2. The noise displays modulations as a function of the gate voltage with extrema appearing exactly at the same gate voltages as for the conductance. Specifically, when the conductance reaches a maximum, the noise reaches a minimum. As the conductance maxima at $V_G = 0.80V$ and $V_G = 1.05V$ are close to 1 in units of $4e^2/h$ (respectively 0.943 and 0.90), the noise almost vanishes, confirming the noiseless character of a fully transmitted fermionic beam *through a carbon nanotube*. After QPCs [2], carbon nanotubes provide a second example of *noiseless* conductors. Another remarkable fact is the quantitative agreement of the measured shot noise with the Fano factor calculated from the quantum shot noise theory. This is also shown in the inset of figure 4a where the normalized noise is represented as a function of the corresponding conductance. As expected, the current noise displays a linear dependence as a function of the conductance in units of $4e^2/h$ which vanished for a transmission close to 1.

We now discuss measurements obtained in the weak backscattering limit which allow in principle a direct determination of the effective charge transferred through the nanotube. Figure 4b displays the noise power spectral density for $V_G = 0.80V$ as a function of $2eI_{BS}\coth(\frac{eV_{sd}}{2k_BT})$ (offset substracted) where $I_{BS} = 4e^2/h\int_0^{V_{sd}} dV(1 - T_{tot}(V))$ is the backscattering current. A linear slope of $F = 0.45 \pm 0.15$ is observed (solid lines). In simple cases however, the slope F should be 1 (dashed lines in figure 4b). Interactions in the Fractional Quantum Hall regime (FQHE) [21] have been shown to strongly reduce F. However, for the case of a single mode quantum wire, a similar renormalization as in the FQHE would imply that the leads are not fermionic [22, 23]. Another possibility would be weak decoherence, possibly induced by the MWNT. Decoherence can indeed be simulated by adding a third terminal to the circuit [1]. In that case, noise can be lowered with respect to the pure two terminal (fully coherent) case. Using the multi-terminal theory of quantum shot noise, we have found that decoherence could produce a reduction of the shot noise in the weak backscattering limit. However, it seems difficult to reduce F down to 0.45 for the parameters of our sample. We however emphasize that, since the backscattering current is deduced and not measured in our experimental setup, we cannot completely rule out a calibration problem of our setup which would produce such a reduced shot noise.

In summary, we have measured the zero frequency shot noise of carbon nanotube based Fabry-Perot interferometers. The noise is modulated as one sweeps the resonant levels through the Fermi energy of the reservoirs and vanishes almost as transmission approaches unity. The data is in quantitative agreement with the non-interacting theory. In the weak backscattering limit, where shot noise is expected to follow the Schottky law with the backscattering current, the noise is found slightly smaller. This may indicate an effect of electron-electron interactions or weak decoherence.

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